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Efficacy and reduced fuel use for hot water weed control on pavements

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Summary

Non-chemical weed control on pavements needs more frequently repeated treatments than the application of glyphosate and often uses large amounts of fuel. To obtain effective hot water control with minimum energy consumption, an in-depth study of efficacy-influencing factors was performed. Three dose–response pot experiments were conducted outdoors to investigate the impact of growth stage (39, 60 and 81 day old), water temperature (78, 88 and 98°C), time of the day (2, 7 and 12 h after sunrise) and treatment interval (2, 3, 4 and 6 week intervals) on hot water sensitivity of seven weed species that are hard to control on pavements. Responses to hot water were quantified by weed coverage and total dry biomass. In general, hot water sensitivity was highest for species with large planophile leaves and lowest for grasses with small erectophile leaves. Most species were twofold to sixfold more sensitive to water at 98°C than at 78 and 88°C, particularly when treated at early growth stages. Among treatment intervals, treating at 3-week intervals was up to twofold more effective and energy efficient than treating at 6-week intervals. Sensitivity was about twofold lower in the morning than in the afternoon. For effective control of weeds, while using less fuel, it is recommended to apply hot water in the late afternoon, to operate at high water temperature (98°C) and to treat plants as young as possible at 3-week intervals.

Keywords: thermal weed control, hot water, hard surfaces, dose–response, treatment interval, energy dose, water temperature, time of the day.

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Introduction

In many European countries, awareness is increasing about the use of pesticides in public urban amenity areas (Kristoffersen *et al.*, 2008). Non-chemical weed control needs more frequently repeated treatments than the application of glyphosate, which causes an almost complete kill of the existing higher plants with one to two treatments a year (Augustin *et al.*, 2001). This makes non-chemical weed control less cost-effective than herbicide spraying. Non-chemical methods often use large amounts of fuel, thus contributing to atmospheric sink effects (Saft & Staats, 2002; Kempenaar *et al.*, 2007). Among non-chemical weeding techniques, hot water causes less wear on the surface (Boonen *et al.*, 2013) in contrast to mechanical weeders. Hot water eliminates the fire hazard associated with flaming (Hansson & Mattsson, 2002) and penetrates better into the vegetation than convective heat (e.g. hot flames and hot air) (Rask & Kristoffersen, 2007). However, the energy consumption per treatment is relatively high, particularly when applied

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non-selectively (Hansson, 2002; Boonen *et al.*, 2013), owing to the high thermal capacity of water. Using precision application technology and precise weed detection, sensors may optimise effective weed control while using less fuel, resulting in a lowered environmental impact (Saft & Staats, 2002; Kempenaar *et al.*, 2007). Contrary to techniques with convective heat transfer, little information is available about specific parameters influencing the efficacy of hot water treatments. According to Hansson and Mattsson (2002, 2003), efficacy (in terms of reduction in above-ground biomass) is influenced by drop size, water flow, water temperature, presence of a wetting agent, rain and drought just before treatment, but not by air temperature in the range 7–18°C. The authors studied these parameters on a single species, *Sinapis alba* L. (white mustard), an annual which is uncommon in paved areas (Fagot *et al.*, 2011). It is well known that plant responses to heat may be species-dependent (Ascard, 1995). In addition, water temperatures tested were all far higher (>100°C) than temperatures (90–100°C) applied by most hot water machines operating in north-western Europe (Kristoffersen *et al.*, 2008; De Cauwer *et al.*, 2013; Rask *et al.*, 2013).

Many plant species with protected meristems, such as grasses and perennial weeds, can regrow after non-chemical treatment (Melander *et al.*, 2009). Hence, these plants should be exhausted by consecutive treatments. There are many reports (e.g. Hansson & Ascard, 2002; Kempenaar & Spijker, 2004; Vermeulen *et al.*, 2006; Rask *et al.*, 2013) on the number of hot water treatments required during an entire season (mostly ranging between 3 and 5 treatments) to keep weeds under control. However, most of these reports do not take into account the total energy requirement during the entire season of the tested weed control strategies. Furthermore, none of these studies investigated efficacy in terms of total (above-ground and below-ground) biomass depletion, although it is well known that the fraction of below-ground biomass in total biomass can be quite high (Anderson, 1999).

So, precise information regarding efficacy of weed control while using less fuel with hot water is lacking for most dominant species growing in paved areas (as indicated by Fagot *et al.*, 2011). We tested the following hypotheses: (H1) species react differently to the applied temperature and their reaction depends on the growth stage, (H2) species show a daytime variation in sensitivity towards hot water, and (H3) the efficacy and fuel efficiency of weed control can be optimised by combining an appropriate treatment interval with an effective energy dose.

Materials and methods

Equipment

All treatments were made with an experimental diesel-powered hot water device. The hot water equipment comprised a stationary heating device with two separate diesel boilers and a hand-pushed four-wheel hot water applicator. This applicator is equipped with a 25-cm-wide water outflow boom with circular 2-mm water outlet holes arranged in a single row, with 6.5 mm between holes. Using 2 mm holes, only big droplets are produced that do not cool down as fast as fine droplets. During spraying, outlet holes were 8 cm above the surface of the pots. The energy dose applied (i.e. the total energy content in the applied hot water per unit treated area, expressed in kJ m^{-2}) depended on water temperature (°C) and spray volume (L m^{-2}). The water temperature at the outlet holes was adjusted by regulating the water flow passing through the diesel boilers. Prior to hot water application, actual water temperature just before the water outlets was checked using a digital thermometer with type-k thermocouple (EAGLE Y137XB, Wellsburg, WV, USA). The spray volume was adjusted by regulating the water flow rate (L min^{-1}) at the water outlet holes and not by varying the travel speed. Water flow was varied by regulating valves and was checked by collecting the outflow water with the aid of an open PVC water pipe attached beneath the outlet holes. The speed of the hot water applicator was kept constant at 2 km h^{-1}, with the aid of a bicycle speedometer mounted to the handlebars of the hot water applicator. So, exposure time was the same in all treatments. Indeed, reducing the variability of exposure time is more important than that of the flow rate in assessing the efficacy of hot water applications (Hansson & Mattsson, 2002).

Test species and growth conditions

Dominant, hard-to-control weeds on pavements as indicated by Fagot *et al.* (2011) were used. The selected weed species were the annuals *Poa annua* L. (annual meadow-grass) and *Conyza canadensis* (L.) Cronq. (Canadian fleabane), and the perennials *Taraxacum officinale* F.H. Wigg. (dandelion), *Plantago major* L. (greater plantain), *Trifolium repens* L. (white clover), *Cerastium fontanum* subsp. *vulgare* (Hartm.) Greuter & Burdet (common mouse-ear) and *Lolium perenne* L. (perennial ryegrass). All species were sown in 350-mL plastic pots filled with a mix of air-dried fine compost and steam-sterilised sandy loam soil containing 2.2%

organic matter, 51.6% silt (2–50 μm), 39.9% sand (>50 μm) and 8.6% clay with a pH-KCl of 5.7. Fine compost was added up to 30% by volume, to mimic *in situ* organic pollution in joints of pavements. This pollution level corresponds with about 6% fine compost by weight, reflecting the actual situation in many old pavements. Indeed, preliminary research indicated that organic matter content (estimated by loss on ignition) in narrow joints (2–5 mm) of 33 old *in situ* pavements ranged between 1.8% and 11.3% by weight, with a median of 5.4%. In all experiments, pots were seeded with 25 seeds per pot at 2 mm depth. As soon as the seedlings had one fully developed true leaf (BBCH stage 11), they were thinned to six uniform plants per pot. Pots were placed on an outdoor concrete floor and irrigated by overhead sprinklers as needed. Prior to hot water application, all pots were placed on a flat concrete surface and arranged in a straight line with a distance between pots of 20 cm. During spraying, pots were kept in the middle of the spraying boom to assure uniform coverage by hot water. After spraying, pots were returned to the outdoor concrete floor.

Dose–response pot experiments

Three dose–response pot experiments were conducted in open air in 2012. In each case, the experimental design was a completely randomised block design with three (Experiments 1 and 2) or six (Experiment 3) replicates. Experiments 1 and 2 were run twice.

Influence of water temperature, plant species and growth stage (Experiment 1)

Impacts of plant species, growth stage and water temperature were determined by exposing 39-, 60- and 81-day-old plants of seven plant species (*P. annua*, *C. canadensis*, *T. officinale*, *P. major*, *T. repens*, *C. fontanum* subsp. *vulgare* and *L. perenne*) to water at 78, 88 and 98°C. Each factorial combination between plant species, water temperature and plant age was tested at 0, 164, 328, 492, 656, 819 and 983 kJ m^{-2} to describe the dose–response relationships. Corresponding spray volumes are provided in Table 1. The different plant ages (expressed as number of days after sowing) were achieved by staggered sowing times. Corresponding growth stages are given in Table 2. These stages represent the stages at which hot water is most commonly applied on pavements. Timings, mean air temperature and solar irradiation data are provided in Table 3.

Influence of time of day (Experiment 2)

Daytime variation in hot water sensitivity was investigated by treating 45-day-old plants of *L. perenne*, *T. officinale* and *C. fontanum* subsp. *vulgare* at 2, 7 and 12 h after sunrise (HAS) with hot water at 98°C. The water temperature of 98°C gave the maximum efficacy in Experiment 1. Each factorial combination between plants species and time of the day was tested at 0, 164, 328, 492, 656, 819 and 983 kJ m^{-2}, to describe dose–response relationships. Details about the growth stages at time of treatment are provided in Table 2. Timings, mean air temperature and solar irradiation data are provided in Table 4.

Influence of treatment interval and cumulative energy dose (Experiment 3)

Impact of treatment interval and cumulative energy dose was studied by treating *L. perenne*, *T. officinale* and *P. major* at 2-, 3-, 4- and 6-week intervals during a period of 12 weeks with hot water at 98°C. *Lolium perenne*, *T. officinale* and *P. major* are all perennial weeds with large below-ground carbohydrate reserves stored in fibrous roots, fleshy taproots or a short rhizome with fibrous adventitious roots respectively (Anderson, 1999). Each factorial combination between treatment interval and plant species was tested at seven cumulative energy doses (i.e. total amount of energy applied per m^2 over a 12-week period), namely 0, 656, 1311, 1967, 2622, 3278 and 3934 kJ m^{-2}. All treatments started on the same date (18 July 2012), at a plant age of 85 days after sowing (23 April 2012). Energy dose per single hot water application varied with cumulative energy dose and treatment interval (Table 5).

Table 1 Spray volume (L m^{-2}) as a function of water temperature and energy dose (Experiments 1 and 2)

Energy dose (kJ m^{-2})	0	164	328	492	656	819	983
Water temperature (°C)							
98	0	0.4	0.8	1.2	1.6	2	2.4
88	0	0.45	0.9	1.35	1.81	2.26	2.71
78	0	0.52	1.03	1.55	2.07	2.59	3.11

Table 2 Plant species per experiment and corresponding growth stage(s) (mean values with standard errors) at time of hot water application (Experiments 1 and 2) or at the time of the first hot water application (Experiment 3)

Plant species	Plant age (days)	Plant height (cm)	Numbers of			
			Leaves	Stolons	Shoots	Inflorescences
Experiment 1*						
Conyza canadensis	81	3.4 ± 0.68	23.8 ± 2.42	–	ND	–
	60	2.1 ± 0.29	17.6 ± 1.21	–	ND	–
	39	2.5 ± 0.52	12.6 ± 0.60	–	ND	–
Lolium perenne	81	8.7 ± 0.37	ND	–	10.4 ± 0.68	–
	60	7.1 ± 0.40	ND	–	7.8 ± 0.58	–
	39	9.0 ± 0.32	ND	–	4.8 ± 0.37	–
Cerastium fontanum	81	ND	ND	–	2.1 ± 0.12	3.2 ± 0.34
	60	ND	ND	–	1.5 ± 0.08	0.9 ± 0.12
	39	ND	ND	–	1.5 ± 0.13	–
Plantago major	81	4.6 ± 0.68	5.4 ± 0.24	–	ND	2.3 ± 0.33
	60	4.0 ± 0.35	4.8 ± 0.37	–	ND	0.7 ± 0.34
	39	4.7 ± 0.49	4.6 ± 0.24	–	ND	0.1 ± 0.07
Taraxacum officinale	81	9.7 ± 0.94	6.8 ± 0.37	–	ND	–
	60	8.5 ± 0.89	6.6 ± 0.51	–	ND	–
	39	6.5 ± 0.32	6.2 ± 0.49	–	ND	–
Poa annua	81	4.6 ± 0.19	ND	–	13.6 ± 0.81	7.8 ± 0.58
	60	3.8 ± 0.34	ND	–	9.0 ± 0.45	4.4 ± 0.24
	39	4.9 ± 0.40	ND	–	6.2 ± 0.58	0.6 ± 0.40
Trifolium repens	81	14.4 ± 1.03	ND	4.4 ± 0.24	ND	1.3 ± 0.30
	60	12.4 ± 0.75	ND	3.6 ± 0.24	ND	0.5 ± 0.17
	39	9.2 ± 0.58	ND	2.5 ± 0.23	ND	–
Experiment 2*						
T. officinale	46	8.0 ± 0.52	5.8 ± 0.31	–	ND	–
C. fontanum	46	ND	ND	–	ND	0.2 ± 0.07
L. perenne	46	9.5 ± 0.43	ND	–	5.7 ± 0.21	–
Experiment 3						
T. officinale	86	6.8 ± 0.38	7.7 ± 0.42	–	ND	–
P. major	86	4.0 ± 0.39	5.2 ± 0.17	–	ND	2.3 ± 0.26
L. perenne	86	8.0 ± 0.52	ND	–	8.3 ± 0.33-	–

ND, not determined.
*Values are means with standard errors, averaged over experimental runs.

Table 3 Mean air temperature and solar irradiation for the selected periods during both experimental runs of Experiment 1

Experimental run	Period	Air temperature (°C)	Daily solar irradiation (GJ cm^{-2})
Run 1	Pre-application		
	19 April*–8 July	14.7	1619
	10 May†–8 July	15.9	1767
	31 May‡–8 July	16.4	1617
	Application		
	9 July, 10:00–11:00	18.9	–
	Post-application		
	10 July–16 July	16.1	1360
Run 2	Pre-application		
	26 April*–15 July	15.3	1621
	17 May†–15 July	16.4	1725
	7 June‡–15 July	16.9	1617
	Application		
	16 July, 10:00–11:00	16.5	–
	Post-application		
	17 July–23 July	16.9	1791

*Sowing date of 81-day-old plants.
†Sowing date of 60-day-old plants.
‡Sowing date of 39-day-old plants.

Table 4 Mean air temperature and solar irradiation for the selected periods during both experimental runs of Experiment 2

Experimental run	Period	Air temperature (°C)	Daily solar irradiation (GJ cm^{-2})
Run 1	Pre-application		
	7 June*–22 July	16.8	1607
	Application		
	23 July, 08:00–08:30	19.8	–
	23 July, 13:00–13:30	28.0	–
	23 July, 18:00–18:30	27.7	–
	Post-application		
	24 July–30 July	19.4	2084
Run 2	Pre-application		
	14 June*–29 July	17.6	1690
	Application		
	30 July, 08:00–08:30	16.0	–
	30 July, 13:00–13:30	24.0	–
	30 July, 18:00–18:30	23.1	–
	Post-application		
	31 July–6 August	18.2	1553

*Sowing date.

Table 5 Energy dose and spray volume per single treatment in function of cumulative energy dose over a 12-week period and treatment interval (Experiment 3)

	Cumulative energy dose (kJ m^{-2}) over a 12-week period					
	656	1311	1967	2622	3278	3934
6-week interval (2)*						
Energy dose (kJ m^{-2} $treatment^{-1}$)	328	656	983	1311	1639	1967
Spray volume (L m^{-2} $treatment^{-1}$)	0.8	1.60	2.40	3.20	4.00	4.80
4-week interval (3)*						
Energy dose rate (kJ m^{-2} $treatment^{-1}$)	219	438	656	874	1093	1311
Spray volume (L m^{-2} $treatment^{-1}$)	0.53	1.07	1.60	2.13	2.67	3.20
3-week interval (4)*						
Energy dose (kJ m^{-2} $treatment^{-1}$)	164	328	492	656	819	983
Spray volume (L m^{-2} $treatment^{-1}$)	0.40	0.80	1.20	1.60	2.00	2.40
2-week interval (6)*						
Energy dose (kJ m^{-2} $treatment^{-1}$)	109	217	328	437	546	656
Spray volume (L m^{-2} $treatment^{-1}$)	0.27	0.53	0.80	1.07	1.33	1.60

*Number of hot water treatments over the 12-week period is mentioned between brackets.

Measurements

Weed inhibitory effect of single hot water treatments was determined by examining species coverage per pot in Experiments 1 and 2 and by total dry biomass in Experiment 3. Species coverage (expressed as number of green pixels per pot) was recorded 7 days after hot water treatment by taking digital photographs of each pot at right angles from a height of 60 cm above the concrete floor and determined using IMAGE J software. In a preliminary study, reduction in species coverage after hot water treatment was highest 7 days after the application date.

Total dry biomass (i.e. the sum of above-ground and below-ground dry biomass, expressed in g pot^{-1}) was determined on 10 October 2013, 14 weeks after the first treatment. Above-ground biomass (except dead tissue) was clipped at surface level and washed prior to drying (24 h at 70°C). Below-ground dry biomass was determined after washing the soil through a 0.2-mm sieve and hand-removal of roots. Roots were dried for 24 h at 70°C.

Data analysis

Data were analysed with the Open Source language and environment R (version R 2.15.1; R Development Core Team, 2012) and its dose–response curves with extension package drc (Knezevic *et al.*, 2007). No significant experimental run by treatment interactions was found for Experiments 1 and 2. Hence, data were pooled before analysis.

All data were subjected to a non-linear regression analysis and were analysed using the three-parameter log-logistic model (Streibig *et al.*, 1993):

$$Y = D/[1 + \exp\{b(\log(X) - \log(E))\}] \qquad (1)$$

where Y is the response (weed coverage, expressed as number of green pixels per pot, in Experiments 1 and 2, and total dry biomass, expressed as g pot^{-1}, in experiment 3), D is the upper limit, and X is the energy dose per single operation in Experiments 1 and 2 or the cumulative energy dose over a 12-week period in Experiment 3. E is the dose resulting in 50% reduction in response between the upper and lower (=0) limit, and B is the slope of the line at the inflection point. Effective dosages ED_{50} (dose required for 50% reduction in weed coverage or total dry biomass) and selectivity indices (SI) as relative potencies between two dose–response curves are commonly used to compare different dose–response curves. They were derived from the regression model utilising the delta method (Van der Vaart, 1998). SI (50, 50) (i.e. the ratio between ED_{50} for one dose–response curve and ED_{50} for another dose–response curve) were used to compare the relative differences of ED_{50} among curves and to deduce the most efficient treatment. Data of Experiments 2 and 3 were Box–Cox-transformed to obtain variance homogeneity.

In addition, all treatment combinations of Experiment 3 were treated as a randomised complete block design with six replicates using ANOVA in R. Treatments comprised all combinations of three plant species with seven cumulative energy doses and four treatment intervals. Due to significant interactions between these experimental factors ($P < 0.05$), the data were split and compared within species. The influence of the treatments on total dry biomass within plant species was analysed by horizontal and vertical comparison of treatment means using one-way ANOVA. Horizontal comparison was conducted by comparing means of treatment intervals within cumulative energy doses. Vertical comparison was conducted by comparing means of cumulative energy doses within treatment intervals. To determine the significant differences between group means, the Tukey HSD test (for normally distributed data) or the Bonferroni test (for non-normally distributed data) was used.

Results

Influence of water temperature, plant species and growth stage

In general, lower ED_{50} dose rates were found when plants were treated with water at higher temperatures, irrespective of the plant age (Fig. 1). ED_{50} dose rates for 39-day-old plants indicated that all plant species except *L. perenne* were twofold to sixfold more sensitive to water at 98°C than to water at 78 and 88°C. The 81-day-old plants were less influenced by water temperature than 39-day-old plants (Table 6). At ED_{50} level, 81-day-old plants were threefold more sensitive to water at 98°C than to water at 78°C, irrespective of plant species except for *C. canadensis*. In contrast to 39-day-old plants, 81-day-old plants were equally sensitive to hot water at 88 and 98°C, except for *C. fontanum* and *P. annua*.

Plant age at application time significantly affected hot water sensitivity at ED_{50} level for *C. fontanum*, *C. canadensis* and *T. officinale*. No effect was found for *P. major*, *L. perenne* and *P. annua* (Fig. 2). ED_{50} dose rate for 39-day-old *C. canadensis* plants was twofold and fourfold lower than ED_{50} dose for 60- and

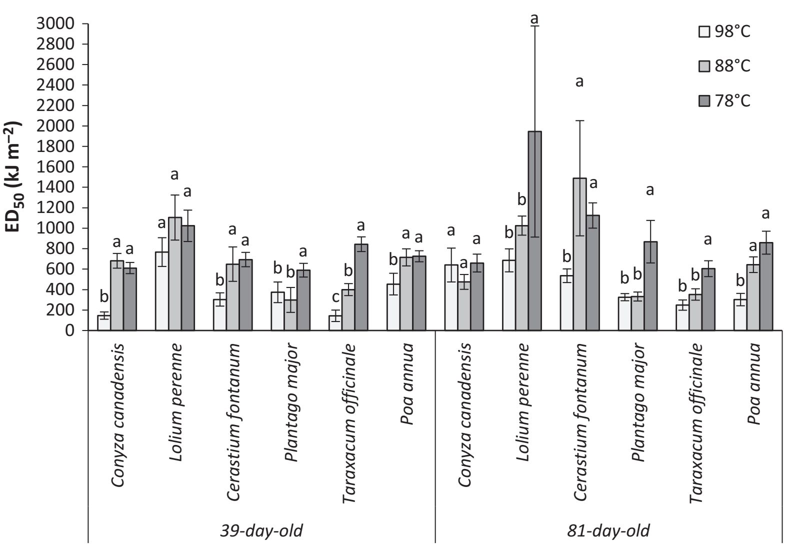

Fig. 1 ED_{50}-responses with standard errors (error bars) for 39- and 81-day-old plant species treated once with hot water at 98, 88 and 78°C (Experiment 1). No significant differences between figures with the same letter (based on computed selectivity indices and corresponding *P*-values); comparison within species and plant ages only.

Table 6 Total (above- and belowground) dry biomass (g pot^{-1}) with (±) standard errors of *Taraxacum officinale*, *Plantago major* and *Lolium perenne* as affected by treatment interval and cumulative energy dose over a 12-week period (Experiment 3)

Plant species	Cumulative energy dose (kJ m^{-2})	Treatment interval			
		6 weeks	4 weeks	3 weeks	2 weeks
T. officinale	0	6.33 ± 0.310a*	6.33 ± 0.310a*	6.33 ± 0.310a*	6.33 ± 0.310a*
	656	4.40 ± 0.381ab*	3.27 ± 0.350b*	3.91 ± 0.409b*	3.67 ± 0.474b*
	1311	3.54 ± 0.633b*	2.84 ± 0.448b*	2.54 ± 0.204b*	2.91 ± 0.251b*
	1967	2.91 ± 0.424b*	2.78 ± 0.434b*	2.19 ± 0.034c*	2.66 ± 0.346b*
	2622	2.62 ± 0.090b*	2.68 ± 0.379b*	2.13 ± 0.251c*	2.93 ± 0.271b*
	3278	2.49 ± 0.065b*,**	2.46 ± 0.159b*,**	1.97 ± 0.162c**	2.94 ± 0.319b*
	3934	2.37 ± 0.354b*,**	2.34 ± 0.330b*,**	1.95 ± 0.175c**	2.93 ± 0.209b*
P. major	0	2.71 ± 0.186a*	2.71 ± 0.186a*	2.71 ± 0.186a*	2.71 ± 0.186a*
	656	2.14 ± 0.419ab*	1.81 ± 0.196ab*	1.43 ± 0.156b*	1.99 ± 0.219ab*
	1311	1.53 ± 0.114b*	1.49 ± 0.248bc*	1.19 ± 0.146b*	1.37 ± 0.112bc*
	1967	1.44 ± 0.062b*	0.95 ± 0.112cd**	1.09 ± 0.167b*,**	1.15 ± 0.081bc*,**
	2622	1.38 ± 0.117b*	0.73 ± 0.076d**	0.99 ± 0.093b*,**	1.10 ± 0.144bc*,**
	3278	1.36 ± 0.099b*	0.64 ± 0.080d**	0.62 ± 0.123c**	0.89 ± 0.143c**
	3934	1.40 ± 0.152b*	0.67 ± 0.042d**	0.53 ± 0.088c**,***	0.31 ± 0.087d***
L. perenne	0	11.31 ± 0.652a*	11.31 ± 0.652a*	11.31 ± 0.652a*	11.31 ± 0.652a*
	656	11.47 ± 0.919a*	10.20 ± 1.779ab*	7.15 ± 0.834b*	8.27 ± 0.614ab*
	1311	8.62 ± 0.919a*	7.32 ± 1.103abc*	6.91 ± 0.216b*	5.79 ± 0.154bc*
	1967	8.66 ± 1.400a*	6.76 ± 1.200bc*	6.11 ± 0.520b*	5.76 ± 0.018bc*
	2622	8.19 ± 0.656a*	5.87 ± 0.354bc**	3.85 ± 0.245c***	5.28 ± 0.359c**
	3278	7.75 ± 0.922a*	5.55 ± 0.485bc*,**	3.72 ± 0.471c**	5.23 ± 0.526c**
	3934	7.62 ± 0.875a*	4.49 ± 0.662c**,***	3.07 ± 0.206c***	5.15 ± 0.257c*,**

Mean values followed by the same letter or number of asterisks are not significantly different at $P = 0.05$ according to the Tukey HSD test (in case of homoscedasticity) or the Bonferroni test (in case of heteroscedasticity). For the letters: comparison within species and treatment intervals only. For the asterisks: comparison within species and cumulative energy doses only.

81-day-old plants respectively. *Cerastium fontanum* and *T. officinale* plants showed twofold lower ED_{50} dose rates when treated at an age of 39 days than when treated at an age of 81 days.

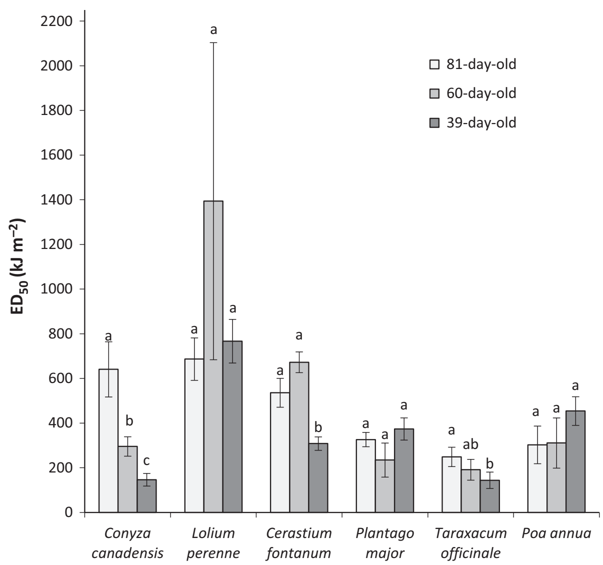

Fig. 2 ED_{50}-responses with standard errors (error bars) for various plant species treated with hot water at 98°C at various plant ages, 39, 60 and 81 days after sowing (Experiment 1). No significant differences between figures with the same letter (based on computed selectivity indices and corresponding *P*-values); comparison within species only.

Huge variation in hot water sensitivity of 39-day-old plants was found among species (Fig. 3). Most sensitive species at ED_{50} level were *C. canadensis* and *T. officinale* exhibiting up to threefold lower ED_{50} values than the least sensitive species *L. perenne* and *P. annua*.

Influence of time of the day

Significant daytime variation in hot water sensitivity was found for all species (Fig. 4). All plant species exhibited more reduction in weed coverage when treated in the afternoon (at 8 and 12 HAS) than when treated in the morning at 2 HAS. There were no significant differences in ED_{50} dose rates among 7 HAS and 12 HAS treatments, irrespective of species. Maximum sensitivity was obtained at 7 HAS for *C. fontanum* and at 12 HAS for *T. officinale* and *L. perenne*. ED_{50} dose rates for *C. fontanum* control were about twofold lower when treated at 7 or 12 HAS than when treated at 2 HAS. *Taraxacum officinale* showed a twofold to 2.5-fold lower ED_{50} dose rate when treated at 12 HAS than when treated at 2 HAS. At 12 HAS, ED_{50} dose rate for *L. perenne* plants was twofold lower than at 2 HAS.

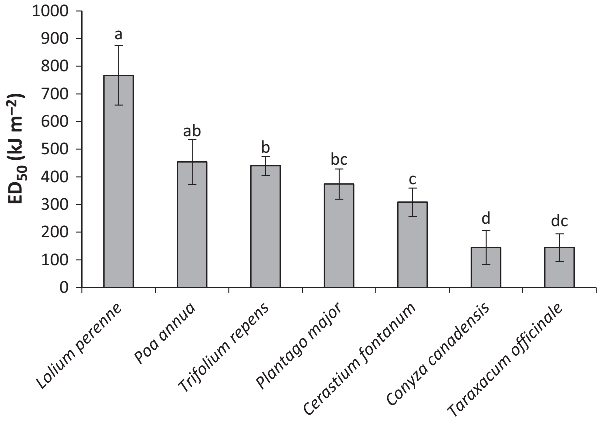

Fig. 3 ED_{50}-responses with standard errors (error bars) for 39-day-old plants of seven species treated once with hot water at 98°C (Experiment 1). No significant differences between figures with the same letter (based on computed selectivity indices and corresponding *P*-values).

Influence of treatment interval and cumulative energy dose

Total dry biomass data of each species showed a significant interaction between cumulative energy dose over the 12-week period and treatment interval (Table 6). Plants treated at cumulative energy doses between 1311 and 3934 kJ m^{-2} had a significant lower total dry biomass than untreated plants, irrespective of plant species or treatment interval. Total dry biomass of treated *L. perenne* and *P. major* plants significantly decreased with increasing cumulative energy dose, irrespective of treatment interval, except for the 6-week interval. In contrast to *L. perenne* and *P. major* plants, *T. officinale* plants were only significantly affected by cumulative energy dose when plants were treated at 3-week intervals.

The most effective treatment interval depended on cumulative energy dose and plant species (Table 6). At cumulative energy doses of 1967 kJ m^{-2} or lower, biomass reduction was not affected by treatment interval, irrespective of plant species, except for dose level 1967 kJ m^{-2} for *P. major*. At the highest energy dose (3934 kJ m^{-2}), total dry biomass was lowest when plants were treated with 3-week intervals for *T. officinale* and *L. perenne*, and with 2-week intervals for *P. major*. No significant difference in total dry biomass was found between 3- and 4-week treatments for *L. perenne*, between 2- and 3-week treatments for *P. major* and 2-, 4- and 6-week intervals for *T. officinale*. Overall, 3-week treatments at an energy dose of 819 kJ m^{-2} per single treatment over a 12-week period (or a cumulative energy dose of 3278 kJ m^{-2}) reduced total dry biomass of *P. major*, *T. officinale* and *L. perenne* plants, relative to the control, by 67.2%, 68.9% and 67.1% respectively.

For *L. perenne* and *T. officinale*, ED_{50} rates were significantly affected by treatment interval (Fig. 5). The ED of *L. perenne* increased with widening treatment interval. Compared with three weekly treated *L. perenne* plants, 4 and 6 weekly treated plants required, respectively, twofold and fivefold higher cumulative energy doses to obtain 50% reduction in total dry biomass. ED_{50} rates were about twofold higher for *T. officinale* plants treated at 6-week intervals than at 3- or 4-week intervals. Within the interval range from 2 to 4 weeks, no significant differences in ED_{50} rates were found for *P. major* despite the low ED_{50} for plants treated at 3-week interval.

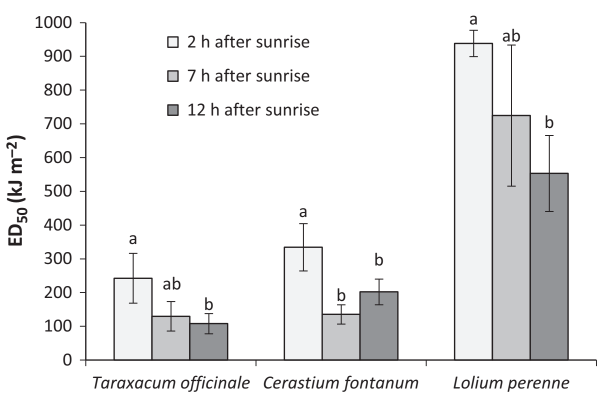

Fig. 4 ED_{50}-responses with standard errors (error bars) for three perennials treated with hot water at 98°C 2, 7 and 12 h after sunrise (Experiment 2). No significant differences between figures with the same letter (based on computed selectivity indices and corresponding *P*-values); comparison within species only.

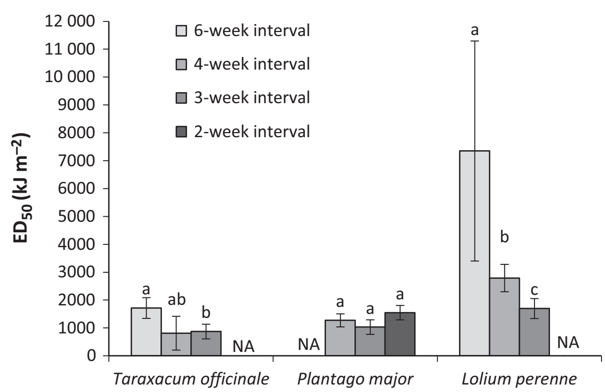

Fig. 5 ED_{50}-responses with standard errors (error bars) for three perennials repeatedly treated during a 12-week period with hot water at 98°C at 6-, 4-, 3- and 2-week intervals (Experiment 3). No significant differences between figures with the same letter (based on computed selectivity indices and corresponding *P*-values); comparison within species only. NA, not applicable, impossible to fit a dose–response curve to the data.

Discussion

All research hypotheses were accepted, as discussed below. A better weed coverage and biomass reduction were obtained at higher water temperature, similar to the findings of Hansson and Mattsson (2002). It took a 1.3- to 5.9-fold lower energy dose to achieve a comparable reduction in weed coverage at 98°C than at 78°C. Indeed, it was only the energy in the water above *c.* 60°C that was effective in killing plants (Hansson & Mattsson, 2002). According to Fourier's law, time rate of conductive heat transfer through a material is proportional to the temperature difference along the path of heat flow. So, the larger the difference in temperature between leaf surface and the applied water, the more lethal the hot water is.

In general, sensitivity to hot water declined with increasing plant age. Thicker wax layers and a higher degree of lignification in ageing plants may be responsible for this (Ascard, 1995). Probably, heat penetration in older plants was also hampered by an umbrella effect. The effect of developmental stage on hot water sensitivity varied widely among species. For *P. major* and *L. perenne*, no significant influence was detected in the plant age range of 39–81 days. The range of tested plant ages may have been supra-optimal for finding sensitivity differences within these species.

In general, young plants were more sensitive than older ones. However, sensitivity varied among species; *L. perenne* and *P. annua* of 39 days old were 3.1- to 5.1-fold less sensitive than *C. canadensis* and *T. officinale*. Grasses have small erectophile leaves causing low water retention and hence high heat losses. The most sensitive species (*C. canadensis* and *T. officinale*) have large, thin planophile leaves with concomitant high specific leaf area (i.e. m^2 of leaf area per unit of leaf dry mass) (Poorter & Remkes, 1990). Such leaves allow high water retention and are easy to heat by conductive heat transfer. Intermediary sensitivity was found for *P. major* and *C. fontanum*. *Plantago major* plants also have large planophile leaves, but leaves are thick and leathery, resulting in a low specific leaf area (Poorter & Remkes, 1990); this may hamper conductive heat transfer and tissue heating above the lethal temperature. *Cerastium fontanum* plants have poorly protected meristems, but leaves are small and thick which make them difficult to heat.

All plant species were more susceptible to hot water treatments in the afternoon (7, 12 h after sunrise) than early in the morning (2 h after sunrise). This cannot be explained by the occurrence of dew, as treatments were executed on plants dry to the touch. Nor can it be explained by differences in air temperature at time of application. According to Hansson and Mattsson (2002) who found no effect of air temperature on hot water efficacy, the cooling effect of transpiration rates (enhanced by higher air temperature) is probably too low to significantly influence tissue heating. Probably, the daytime variation in hot water sensitivity may reflect the daytime variation in leaf relative water content (i.e. the ratio between the amount of water in the leaf tissue at sampling to that present when fully turgid). It is well known that leaf relative water content varies during daytime with highest values in the early morning and late evening and lowest values in the early afternoon depending on air temperature, relative humidity and light intensity (Saini & Rathore, 1982). The more water in the plant, the more energy is needed to increase the plant temperature to the plant-lethal temperature. In a flaming experiment with four species, Ulloa *et al.* (2012) found greatest plant injury and fresh biomass reduction when flaming was performed about 7 h after sunrise, that is when plants had the lowest leaf relative water content. However, daytime variation in relative water content is probably not the only explanatory factor involved. The time during the afternoon (within 7–12 h after sunrise) when plants were most sensitive to hot water was species-dependent. In contrast to *C. fontanum* with highest sensitivity 7 h after sunrise, *L. perenne* and *T. officinale* showed highest sensitivity 12 h after sunrise; at this time, relative water content is expected to increase again owing to a declining transpiration. Daytime variation in hot water sensitivity may be smaller in plants growing under high water stress (e.g. plants growing in *in situ* joint filling material during dry spells). These plants may show lower daytime variation in leaf relative water content, due to smaller stomatal aperture (Šurbanovski *et al.*, 2013).

In general, poorest control (in terms of reduction in total dry biomass relative to the untreated control) was achieved when *P. major*, *T. officinale* and *L. perenne* plants were treated at 6-week intervals, irrespective of cumulative energy dose or plant species. An exception was *T. officinale*, with poorest control when treated at 2-week intervals at a cumulative dose between 2622 and 3934 kJ m^{-2}. In general, biomass reduction increased with increasing cumulative energy dose and with shorter treatment intervals. Reduction in biomass was highest when treated every two weeks (for *P. major*) or every three weeks (for *L. perenne* and *T. officinale*). A short treatment interval may maximise the depletion of plant carbohydrate and nutrient sinks by killing most of the above-ground photosynthetically active regrowth tissues before plants are able to refill their below-ground carbohydrate reserves. In addition, above-ground plant injury per single treatment may be higher due to higher heat sensitivity of younger tissue and higher heat penetration through a less-dense canopy (Ascard, 1995).

Highest efficiency (or lowest dose rate for equal weed control) was obtained when *P. major*, *T. officinale* and *L. perenne* were treated every 3 weeks. Overall, 70% depletion of total dry biomass, relative to the control, was obtained when plants were treated at 3-week intervals with a dose rate per single treatment of around 819 kJ m^{-2}. Unfortunately, in practice, the choice of treatment interval is commonly determined by practical and economic factors (other than energy costs), rather than by considerations about efficacy relative to energy use. At the same cumulative energy dose, administrators/contractors will prefer longer treatment intervals over shorter, because annual treatment costs are determined more by labour costs and yearly machine depreciation than by energy costs (Boonen *et al.*, 2013) and because of the reduced need to impose parking bans and reduced access to enable treatments. In the long run, treating plants with large intervals may be counterproductive due to insufficient depletion of the weeds.

None of the perennial weeds tested were killed after a 12-week period of consecutive hot water control, irrespective of treatment interval. At the end of the 12-week period, total above-ground and below-ground dry biomass relative to the untreated control was still about 30% (Table 6). This is attributable to the large root system of species tested; at the end of the 12-week period, the share of below-ground dry biomass in total dry biomass was still 65%, 75% and 92% for untreated *L. perenne*, *P. major* and *T. officinale* plants respectively. Hence, more treatments are required to fully deplete below-ground storage organs. In early spring, hot water control should be resumed as soon as regrowth starts and repeated with a 3- to 4-week interval, particularly during the active growth period of the weeds, to further deplete plant's carbohydrate and nutrient reserves stored in below-ground organs. As repeated use of a single technique is likely to cause flora shifts to more heat-tolerant species (Fagot *et al.*, 2011), sequences of different weed control techniques applied at short treatment intervals would be preferred. Overall, the results indicate that to achieve effective control of weeds, in particular grass and perennial weeds, with optimal energy use, hot water applications should be made in the afternoon, at high water temperature (98°C), to plants as young as possible and repeated at 3-week intervals.

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References

Anderson WP (ed.) (1999) *Perennial Weeds: Characteristics and Identification of Selected Herbaceous Species*. Iowa State University Press, Ames, IA, USA.

Ascard J (1995) *Thermal Weed Control by Flaming. Biological and Technical Aspects*. Doctoral thesis, Swedish University of Agricultural Sciences, Alnarp, Sweden, Report 200.

Augustin B, Fischer E & Seibel H (2001) Möglichkeiten der Vegetationskontrolle auf Nicht-Kulturland [Possibilities of weed control in urban areas. With English summary]. *Gesunde Pflanzen* **53**, 169–176.

Boonen E, De Cauwer B, Fagot M, Beeldens A & Reheul D (2013) *Handleiding voor Niet-chemisch(e) Onkruidbeheer (sing) op Verhardingen met Kleinschalige Elementen. OCW Aanbevelingen A84/12*. Belgian Road Research Centre, Brussels, Belgium.

De Cauwer B, Fagot M, Beeldens A, Bulcke R & Reheul D (2013) Integrating preventive and curative non-chemical weed control strategies for concrete block pavements. *Weed Research* **54**, 97–107.

Fagot M, De Cauwer B, Beeldens A, Boonen E, Bulcke R & Reheul D (2011) Weed flora in paved areas in relation to environment, pavement characteristics and weed control. *Weed Research* **51**, 650–660.

Hansson D (2002) *Hot Water Weed Control on Hard Surface Areas*. PhD thesis, Department of Agricultural Engineering, Swedish University of Agricultural Sciences, Alnarp, Sweden.

Hansson D & Ascard J (2002) Influence of developmental stage and time of assessment on hot water weed control. *Weed Research* **42**, 307–316.

Hansson D & Mattsson JE (2002) Effect of drop size, water flow, wetting agent and water temperature on hot-water weed control. *Crop Protection* **21**, 773–781.

Hansson D & Mattsson JE (2003) Effect of air temperature, rain and drought on hot water weed control. *Weed Research* **43**, 245–251.

Kempenaar C & Spijker JH (2004) Weed control on hard surfaces in The Netherlands. *Pest Management Science* **60**, 595–599.

Kempenaar C, Lotz LAP, van der Horst CLM, Beltman WHJ, Leemans KJM & Banninck AD (2007) Trade off between costs and environmental effects of weed control on pavements. *Crop Protection* **26**, 430–435.

Knezevic SZ, Streibig JC & Rits C (2007) Utilizing R software package for dose–response studies: the concept and data analysis. *Weed Technology* **21**, 840–848.

Kristoffersen P, Rask AM & Larsen SU (2008) Non-chemical weed control on traffic islands: a comparison of the efficacy of five weed control methods. *Weed Research* **48**, 124–130.

Melander B, Holst N, Grundy AC *et al.* (2009) Weed occurrence on pavements in five North European towns. *Weed Research* **49**, 516–525.

Poorter H & Remkes C (1990) Leaf area ratio and net assimilation rate of 24 wild species differing in relative growth rate. *Oecologia* **83**, 553–559.

R Development Core Team (2012) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. Available at: http://www.R-project.org (last accessed 10 May 2013).

Rask AM & Kristoffersen P (2007) A review of non-chemical weed control on hard surfaces. *Weed Research* **47**, 370–380.

Rask AM, Larsen SU, Andreasen C & Kristoffersen P (2013) Determining treatment frequency for controlling weeds on traffic islands using chemical and non-chemical weed control. *Weed Research* **53**, 249–258.

Saft RJ & Staats N (2002) *Beslisfactoren voor onkruidbestrijding op verhardingen 'LCA, risico-analyse, kostenanalyse en hinderbeleving*. IVAM Environmental Research b.v., University of Amsterdam, Amsterdam, the Netherlands.

Saini BC & Rathore TR (1982) Diurnal changes in water deficit and recovery patterns of intact rice leaves under natural and controlled environment conditions. *Biologia Plantarum* **25**, 331–335.

Streibig JC, Rudemo M & Jensen JE (1993) Dose–response curves and statistical models. In: *Herbicide Bioassays* (eds JC Streibig & P Kudsk), 29–55. CRC Press, Boca Raton, Florida, USA.

Šurbanovski N, Sargent DJ, Else MA, Simpson DW, Zhang H & Grant OM (2013) Expression of *Fragaria vesca PIP* aquaporins in response to drought stress: *PIP* down-regulation correlates with the decline in substrate moisture content. *PLoS ONE* **8**, e74945.

Ulloa SM, Datta A, Bruening C, Gogos G, Arkebauer TJ & Knezevic SZ (2012) Weed control and crop tolerance to propane flaming as influenced by time of day. *Crop Protection* **31**, 1–7.

Van der Vaart AW (1998) *Asymptotic Statistics*. Cambridge University Press, Cambridge, UK.

Vermeulen GD, Verwijs BR & Kempenaar C (2006) *Effectiveness of Weed Control Methods on Pavement*. Plant Research International, Wageningen, the Netherlands.